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Technical Direction and Evaluation of Cost Analysis for Space System Studies

MAY 1967

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Los Angeles, California

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TECHNICAL DIRECTION AND EVALUATION OF COST ANALYSIS FOR SPACE SYSTEM STUDIES

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FOREWORD

This report is published by Aerospace Corporation, El Segundo, California, under Air Force Contract No. AF 04(695)-1001. The report was authored by Joseph A. Neiss of the System Planning Division at El Segundo Technical Operations and Herbert Brown of the Space Systems Division, Air Force Systems Command.

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This report contains no classified information extracted from other classified documents.

Approved

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

Economic and cost effectiveness analyses of proposed system concepts have become vital requirements in virtually all U. S. Air Force Space Systems Division studies. Since development of a space system is extremely costly, lead time is lengthy, and budget limitations are severe, there is a clear need to forecast the total systems cost and effectiveness of a proposed new system as early in the planning cycle as possible.

This report presents highlights of the significant aspects of technical direction efforts in systems cost and cost effectiveness analyses. Major objectives of this effort are to ensure that the industry contractor:

a. Performs a total system cost analysis of sufficient depth and validity to permit analysis and evaluation

b. Identifies those operational design and hardware concepts which will provide the greatest savings in total systems cost

c. Properly validates those significant concepts and cost relationships which will lead to the selection of an optimum configuration

Recommendations on the approach and techniques to fulfill these objectives are provided. The uses and limitations of industry cost models, cost estimating relationships, and other estimating methods are discussed. Common pitfalls in systems cost analysis are illustrated to indicate the guidance necessary.

A combination of engineering and economic analysis experience and skills is shown to be a vital requisite to proper accomplishment and validation of the industrial contractor's effort.

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1. INTRODUCTION

Economic and cost effectiveness analyses of proposed system concepts have become vital requirements in virtually all U.S. Air Force Space Systems Division (SSD) studies, as they have for many other military systems. Since development of a space system is extremely costly, lead times are lengthy, and budget limitations are severe, there is a clear need to forecast the total systems cost and effectiveness of a proposed new system as early in the planning cycle as possible. While the cost analysis task in these studies is generally small in effort (normally 10 to 20 percent of the total technical planning tasks), its impact on the development decision may be the decisive element. It is, therefore, important that regardless of its size, this task be well defined, organized, and effectively carried out.

The systems cost analysis task generally required of industrial contractors undertaking planning studies is usually directed toward determining the total cost to the U. S. Air Force for developing, acquiring, and operating a proposed system or systems. These cost estimates serve as guidelines for future program planning and provide a basis for selection between competing system configurations.

The SSD responsibility in space system studies encompasses the entire spectrum of study requirements from conceptual formulation to evaluation of study results. The SSD and Aerospace Corporation function together as a composite team in the formulation of study requirements which include the development of specific work statements. This team also carries out the evaluation of industrial contra[illegible] proposals.

Selection of industry contractors is the responsibility of SSD. After contract award, the industrial contractor becomes an integral part of the study team, with the Aerospace Corporation providing the technical direction.

Aerospace Corporation efforts in technical direction and evaluation of space system studies are directed toward assisting SSD in organizing and defining the industry effort which will fulfill the objectives of the approved study program. Major objectives of this assistance are to ensure that the industrial contractor:

a. Performs a total system cost analysis of sufficient depth and validity to permit analysis and evaluation.

b. Identifies those operational design and hardware concepts which will produce the greatest savings in total systems cost.

c. Properly validates those significant concepts and cost relationships which will lead to the selection of an optimum configuration.

Technical direction requires a broad knowledge of both engineering and economic considerations. It is best performed when close coordination is established between the various engineering and economic analysis groups within the agency carrying on the technical direction and the industrial contractor performing the study. While a good understanding of engineering concepts and system requirements may serve as a basis for judging the adequacy of the industry contractors' effort, a similar understanding of the technical aspects of system cost analysis is also necessary. This technical costing direction is important to ensure that those who prepare the cost data, those who evaluate the data, and those who may eventually use the data have the same understanding of the technical concepts on which the costs are based including their limitations and degree of reasonableness.

The approach taken in the technical direction aspects of cost studies, while allowing ample room for "engineering judgment," focuses attention on key mission-oriented costing issues rather than on masses of cost detail. It recognizes that system concepts and hardware designs are usually not defined in terms of detailed specifications and requirements. It also acknowledges that the ground rules, definitions, and assumptions applied by the industrial contractor are as important as the numerical results.

There are no magic industry cost formulas, cost models, cost effectiveness solutions or estimating methods which will develop total system costs and also meet the objectives of the cost analysis of every space system. Each proposed system concept must, therefore, be carefully analyzed for cost considerations on the basis of preliminary plans for development, procurement, operation, and system support characteristics. The industrial contractor's study effort must also be of sufficient depth to ensure that promising alternative system concepts are not eliminated until their economic potential can be validated. By employing explicit evaluation methods and techniques, it is hoped that costly technical efforts will be directed toward system concepts that show good economic potential. The choice of cost estimating methods for conceptual type studies, which are covered by the technical direction effort, is influenced by the purpose of the estimate, the level of technical and cost information available, and the costing capability of the industrial contractor in each case.

This report highlights the significant aspects of technical direction efforts in systems cost analysis of space system studies. It provides some recommendations on the approach and techniques to initiate the industrial contractors' systems cost analyses, review their progress, and evaluate their final reports. As additional experience is acquired, a growing foundation will result from which principles and practices may be drawn to further improve future efforts.

2. BACKGROUND OF TECHNICAL DIRECTION AND EVALUATION OF SPACE SYSTEMS COST STUDIES

Systems engineering and technical direction must be performed in today's economy within the framework of a realistic economic forecast. This important role of the Aerospace Corporation is to serve as a link between the government that sets the requirements for national defense and industry that fulfills those requirements with developmental, manufacturing, and managerial skills.

The Department of Defense (DOD) programming system is the basic financial decision-making procedure for systems acquisition. Economic analyses support this programming system by providing cost estimates that are consistent with the analytical and planning objectives of this procedure. To assure consistency, each principal area of technical risk and cost uncertainty needs to be identified, analyzed, and evaluated for its cost impact. This procedure also applies to decisions involving modifications and changes to existing programs.

The SSD has recently conducted several contractor studies involving plans for new launch vehicles and space vehicles. These studies emphasize the use of economic analyses to arrive at sound technical system characteristics and performance factors. The contractor's economic analysis has, therefore, become a critical part of the study effort. To ensure a reasonable and valid analysis, a considerable effort must be directed toward the development of adequate costing definitions, methodology, and ground rules.

A major objective of the technical direction effort is to show the over-all economic implications of a proposed system and to identify the relationships between cost and system performance which form the basis for evaluating the merits of the proposed system. Generally, these forecasts will form the framework of proper program definition, development, acquisition, and operation of any new system.

3. STEPS IN INITIATION OF TECHNICAL DIRECTION OF CONTRACTOR EFFORT

The request for proposal (RFP) work statements and definitions furnished to prospective industrial contractors for conceptual studies are primarily intended to indicate the general scope of the study effort and the major tasks to be accomplished. The language of the requirement contained in the RFP relating to the system cost analysis and cost effectiveness requirements is usually limited to a basic definition of nonrecurring and recurring costs, major system cost elements, and general objectives of the cost analysis.

It is often not possible to adequately define the specific parameters of the program that are to be costed until the industry proposals have been evaluated. This proposal evaluation and selection process combines SSD requirements and objectives and the industry response into a definitized study contract.

An example of the study flow and task requirements from a current space system study is illustrated in Fig. 1. As can be seen, the cost analysis task links the spacecraft requirements and operation and vehicle system preliminary design to the vehicle evaluation. This cost analysis effort differs substantially from the type of cost analysis found in industry proposals for carrying out specific development and production programs. In system studies, the cost analysis is employed as an aid to vehicle selection and evaluation and, in addition, serves to project total system cost for budget planning.

3.1 DEFINING THE SPACE SYSTEM TO BE COSTED

So that the industrial contractor, SSD, and Aerospace will have a clear understanding of the scope of the program to be costed, a comprehensive program plan is negotiated with the contractor prior to or at the beginning of the study. The cost elements of a space system must be compatible with the definitions used by the Air Force Systems Command (AFSC) and DOD.

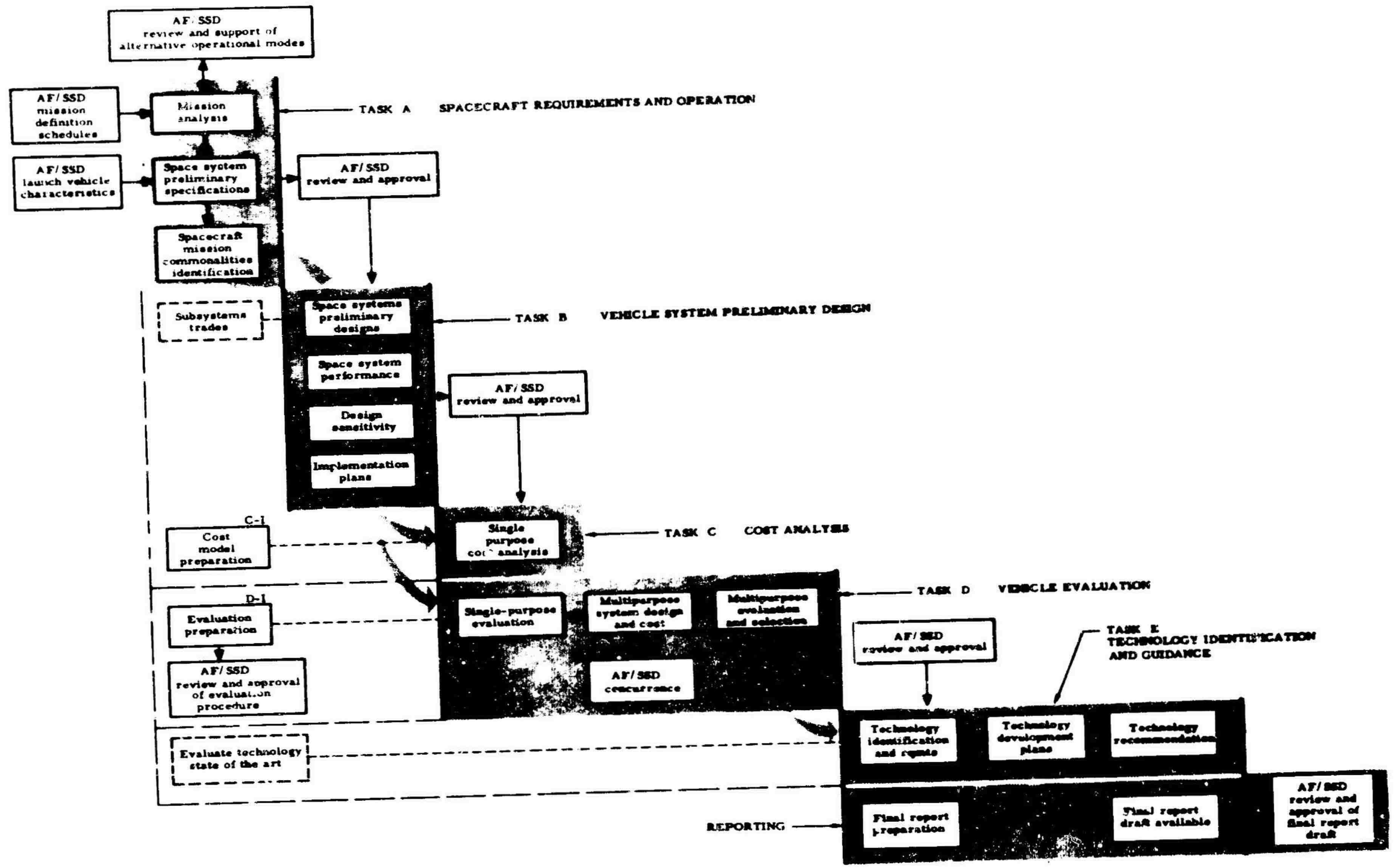


Fig. 1. Example of Study Flow for a Space Vehicle Study Program (Ref. 1)

A summary and brief description of the characteristics of selected space system cost elements has been prepared by the Office of Secretary of Defense. This definition is included in Appendix A along with an example of definitions of cost categories and cost elements for a space system which was recently developed by SSD, Aerospace, and the contractor for use in a specific study. This definition divides the major cost categories into:

a. Research, development, testing, and evaluation costs
b. Initial investment costs
c. Operational costs

Each cost element within each major cost category is accompanied by a brief description of what cost items or types of cost are included together with specific examples for clarification. Various design, development, testing, manufacturing, and system support activities are also readily outlined. With this degree of definition as a foundation, the scope of the costing program and the system cost analysis effort can be made clear to the contractor.

It is important to note that the industrial contractor should be expected to provide an explicit estimating approach to each of these cost elements. In this approach the methods, techniques, and data that the contractor expects to utilize should be outlined.

These categories and definitions have been specifically developed for use in conceptual studies and are not as complete or as specific in context as is usually found in subsequent program definition phases. The level of funding, technical definition, and schedule for this type of effort does not allow for the cost detail expected in a subsequent project definition phase (PDP).

The type of study performed may also require an assumption as to whether a comprehensive RDT&E program is essential to meet the technical requirements of the system under study. This will require the contractor to provide a summary of the research and development background and technology

required to develop the system. The summary should also include a brief description of the major subsystems and an analysis of program objectives and reliability requirements.

The RDT&E program concepts may also assume that technical feasibility is verified before a commitment to a production program is made. This assumption affects the program schedule and may require a comprehensive ground and flight test program to qualify all equipment and systems.

3.2 ESTABLISHING THE GROUND RULES

In addition to understanding the definition of program content, there must also be agreement among SSD, Aerospace, and the industrial contractor concerning the ground rules covering the systems cost analysis. This is significant because in developing total systems cost, the industrial contractor must cover all aspects of normal prime contractor effort, government furnished systems, and military costs. In costing military items, it is important that such categories as facilities, operations services, and logistic support be included and separately identified.

The systems cost analysis should emphasize the major cost aspects of the space systems that are applicable to the study. The space system may be a spacecraft, a reentry vehicle, a launch vehicle, or a combination of these. The subsystems to be costed may include the structure, thermal protection, guidance and navigation, electrical power, environmental control, reaction control, propulsion, communications, instrumentation, and crew systems that are applicable to the type of system and vehicle.

Other aspects of costs, such as systems engineering, ground and flight testing, AGE, and program management, also require identification. Systems support costs such as ground and tracking station and recovery operations are other areas to be emphasized.

The costing of a space system is a complex task; its magnitude is indicated by Figs. 2 and 3. These figures include aspects of direct and indirect operating costs and illustrate the magnitude of the costing effort and the need for establishing ground rules. Problems arise in that industrial contractors may be limited in their background and cost history to reasonably project many of these cost items. In addition, the main objective of the study is usually the vehicle system which encompasses much of the resources allocated. Proper costing of these categories and elements requires close coordination and cooperation among the SSD project office, Aerospace, and the industrial contractor.

An understanding of the price level changes upon which the system cost analysis is to be based is also necessary. Most cost studies are in constant dollars for the year in which the study is conducted. However, in certain instances, costs in escalated dollars for the time period of the program may be desired.

In some studies, costs of certain related systems or equipment do not fall within the scope of the contractor's study efforts or may be so highly uncertain that it is desirable to provide the industrial contractor with recommended values. This approach is often necessary in estimating mission equipment or payload costs, or in parallel studies to establish uniform costs for certain system support and military costs.

3.3 REVIEWING THE CONTRACTOR'S HISTORICAL COSTS AND COST APPROACH

The historical cost data being utilized by the contractor as a basis for his cost projections must be reviewed to determine its applicability to the study program. Initial effort is directed toward ascertaining whether the industrial contractor's personnel are familiar with the system descriptions, program scope, and technical parameters which the cost data reflect, and also whether they are familiar with the industrial contractor's accounting or cost reporting system.

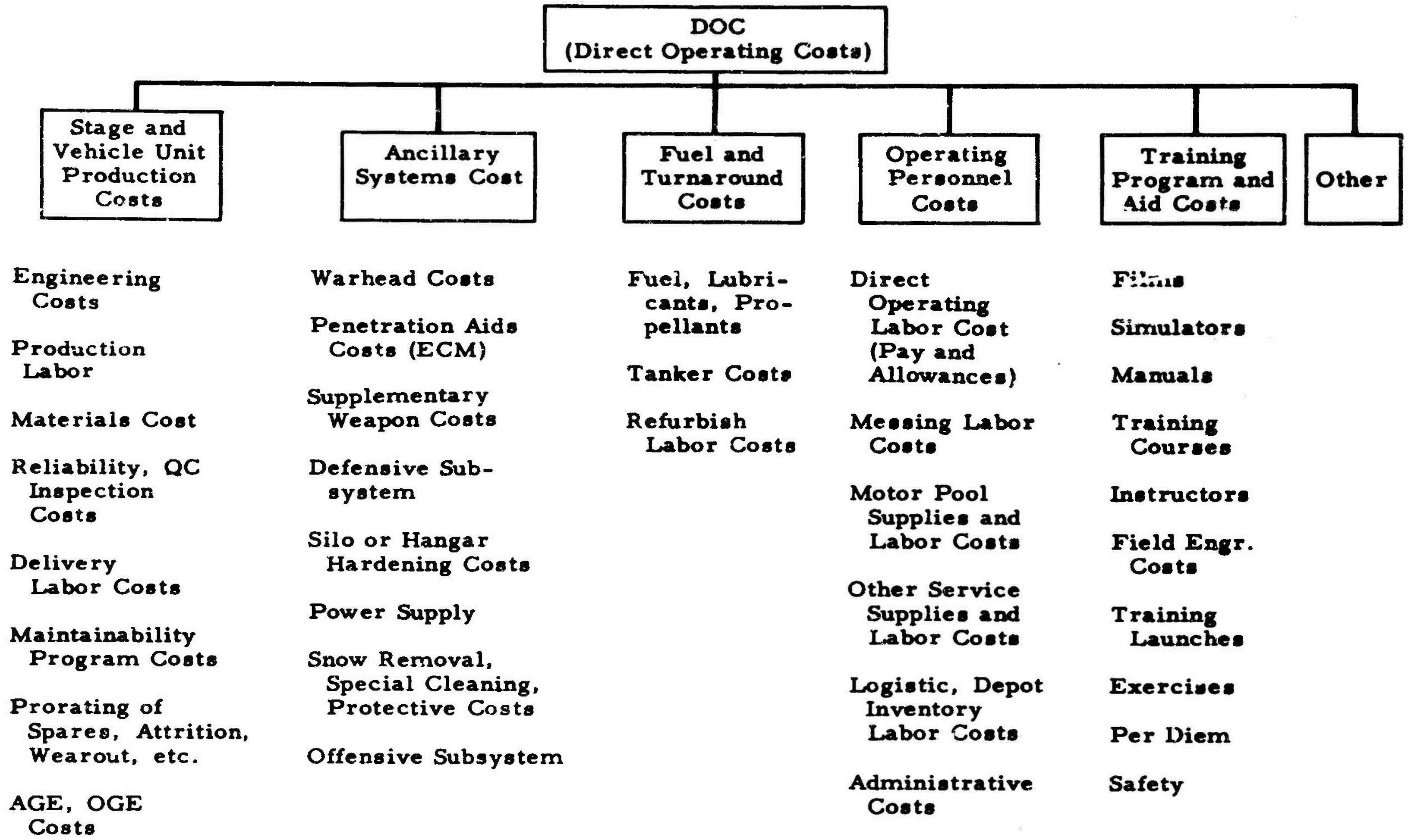
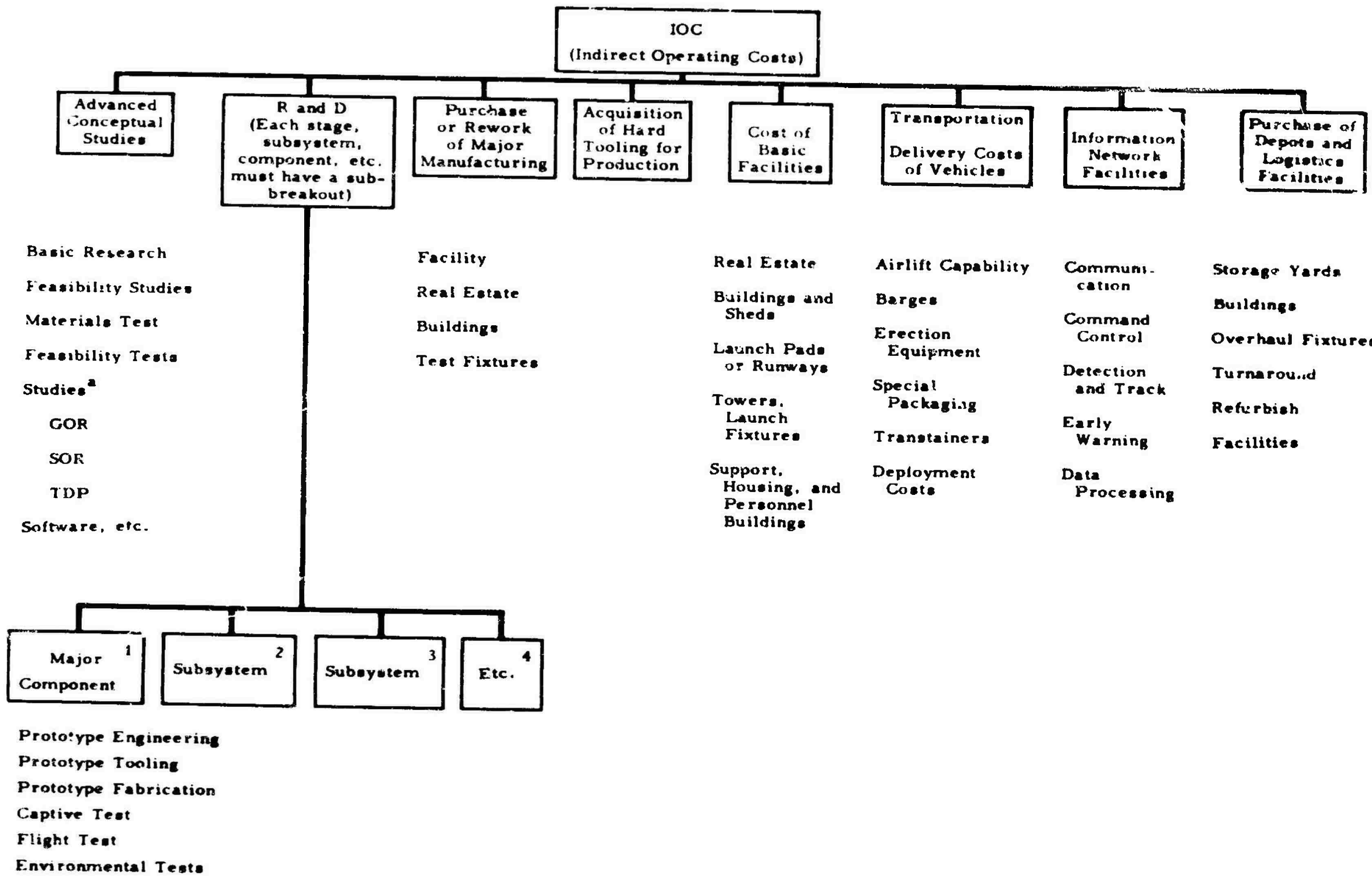


Fig. 2. Aspects of Direct Operating Costs (Ref. 2)



[a]GOR – General Operating Requirement
SOR – Specific Operating Requirement
TDP – Technical Development Plan

Fig. 3. Aspects of Indirect Operating Costs (Ref. 2)

In addition, the personnel should be aware of the variations between original versus final costs, changes to the program, unusual technical problems that may impact on costs and the cost elements, and cost categories of the work breakdown structure. Much of the confusion in using cost history lies in defining and adequately understanding the information that is actually reflected in the costs being used for estimating purposes.

Historical data may be the actual costs of specific systems and specific programs. It may be the various cost relationships derived from a composite of programs or recent proposal estimates. It may also be the specific cost estimating relationships (CER's) obtained from relationships between cost and system performance or technical characteristics, since each military system has a number of physical characteristics that affect cost, performance, and effectiveness.

Table 1 lists, by subsystem, examples of technical parameters which can be used to derive CER's. By using CER's for subsystem elements, the data and time required to develop such estimates are greatly minimized. However, CER's derived from historical data are valid only when basic system characteristics do not substantially change.

A general example of a CER for liquid propellant engines is illustrated in Fig. 4. To use this CER requires that the engine vacuum thrust and the type of feed system be known. Table 2 lists another type of CER which shows dollars per kilowatt for alternative space power subsystems based on present capabilities. The dollars per kilowatt are shown to be functions of the type of subsystem, design life, efficiency, and specific weight and size. Since technology in space power systems is advancing rapidly, recent SSD studies have developed considerable new cost data and CER's. When using CER's it is important to take into consideration the cost variances that result from expanded technology and production of systems.

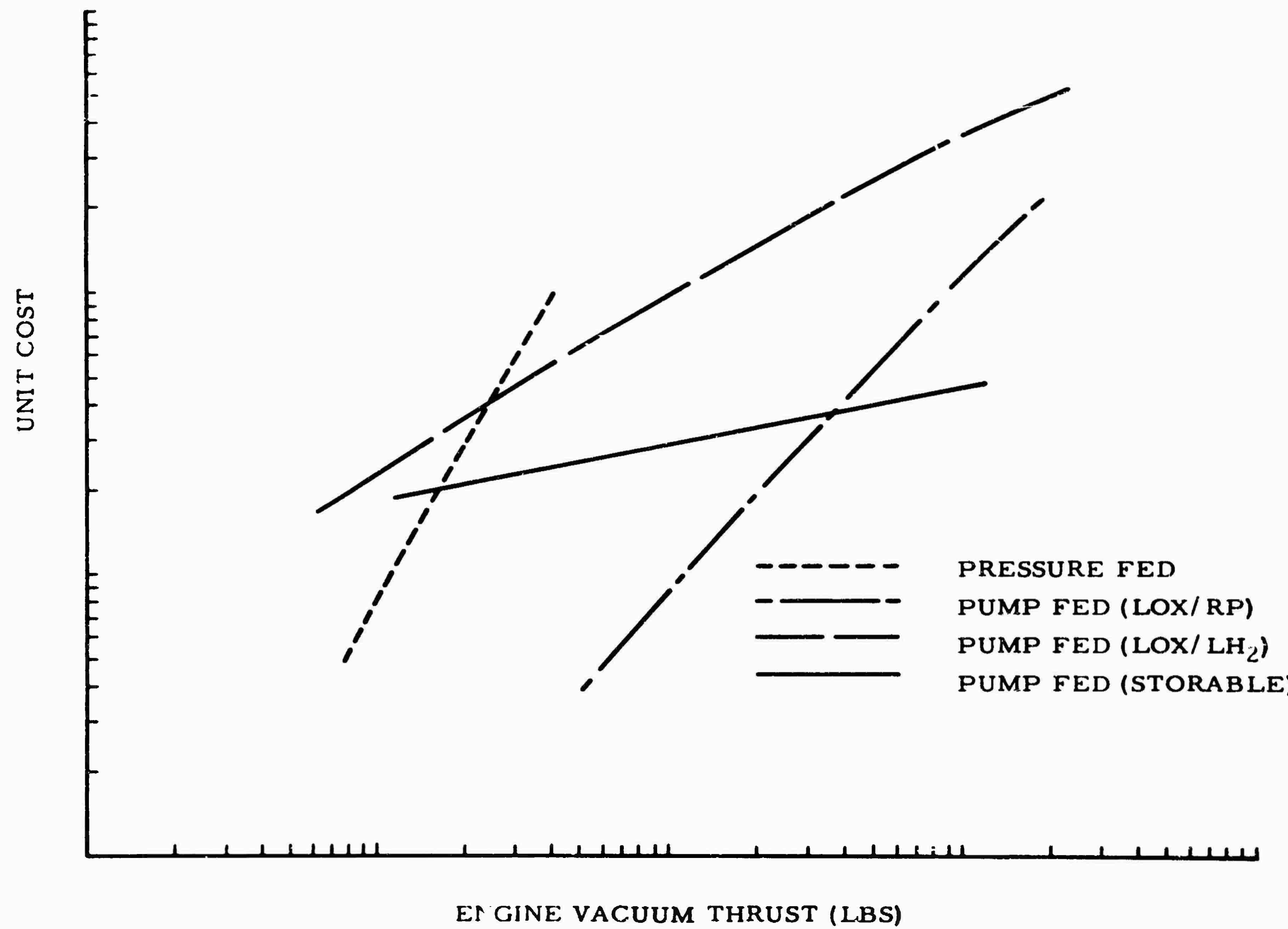


Fig. 4. Cost Estimating Relationship for Liquid Propellant Engines (average unit procurement cost versus engine vacuum thrust)

Table 1. Technical Parameters Affecting Costs

Subsystem	**Capacity, Size and Type** Related to physical properties, load placed on subsystem, and type of construction or material	**Efficiency, Accuracy, and Sensitivity** Index of how well a subsystem performs its assigned functions	**Functions, Requirements, Shape** Number of functions that a subsystem must perform; number of equipment items served by a subsystem
Structure	Diameter Volume Weight Material composition	Ratios: Volume to structure weight Useful load to structure weight External load to structure weight	Shape: Conical, truncated conical and cylindrical modules
Propulsion	Total impulse Weight of propellant Weight of system (inert) thrust The mass of the module(s) to be propelled by ΔV requirements	$\frac{I_{sp} \text{ (actual)}}{I_{sp} \text{ (ideal)}}$	Throttling ratio Number of starts
Environmental Control	Subsystem weight Pounds of oxygen available Man-days Maximum oxygen flow rate Equivalent pounds of O_2 required Equivalent pounds of CO_2 removal capability	Emergency flow rate to normal gas flow rate Man-days/subsystem weight Btu/hr/subsystem weight	The number of ECS pressure levels + number of loads on subsystem Number of men
Stabilization and Control	Weight of subsystem Launch weight of vehicle	Permissible errors: Pitch, roll, and yaw Minimum attitude change rate	Number of major maneuvers
Reaction Control	Total impulse Subsystem weight (Mass of modules to be propelled by ΔV requirements)	$\frac{I_{sp} \text{ (actual)}}{I_{sp} \text{ (ideal)}}$	Mono- vs bipropellant Number of thrust chamber assemblies
Guidance and Navigation	Capacity of computer Weight of subsystem	Permissible error: Position, Velocity, Vector Time between fixes	
Electrical Power	Total kilowatt-hours for mission Peak power requirement Nominal power required Subsystem weight Number of critical events	Kilowatt-hours per pound of subsystem weight	Number of subsystems requiring power Number of experiments requiring power
Communications	Subsystem weight Number of components Transmitter power output Maximum operating distance Number of critical events	Maximum operating distance/subsystem weight Receiver performance $\left(\frac{S+N}{N}\right)$	Crew size Number of subsystems
Instrumentation	Number of measurements Number of data channels Number of crew stations	Ratio: Number of measurements to subsystem weight	Number of subsystems
Crew Systems	Number of crewmen Number of crew stations Subsystem weight Mission duration	Man days/subsystem weight Man days/pressure cabin volume Number of crewmen/pressure cabin volume	Number of controls and displays

Table 2. Cost Estimating Relationship - Space Power Subsystems' Present Capabilities (Ref. 3)

Subsystem	Efficiency (percent)	Specific Weight (lb/kw)	Specific Size (cu ft/kw)	Specific Cost (dollars/kw)
Primary Batteries[a]				
10 min	14	3.0	0.01	50
1 hr	24	18.5	0.06	310
24 hr	34	315.0	1.10	5,300
1 wk	40	1,960.0	6.62	31,900
Solid Propellant APU				
1 kw for 1 min	22	16.0	0.03	10,000
1 kw for 10 min	22	24.0	0.11	10,000
100 kw for 1 min	30	3.2	0.01	1,000
100 kw for 10 min	30	5.1	0.03	1,000
Hydrogen-Oxygen APU[b]				
1 kw for 10 min	18	26.0	0.22	24,000
1 kw for 1 wk	18	1,120.0	172.00	350,000
100 kw for 10 min	30	4.5	0.13	21,000
100 kw for 1 wk	30	495.0	72.00	220,000
Hydrazine APU				
1 kw for 10 min	18	27.0	0.07	21,000
1 kw for 1 wk	18	1,786.0	23.80	110,000
100 kw for 10 min	30	5.0	0.06	20,000
100 kw for 1 wk	30	1,064.0	14.30	71,000
Hydrogen-Oxygen Fuel Cell[c]				
High Power Density 1 hr	50	42.0	1.10	30,000
High Power Density 24 hr	50	70.0	3.00	35,000
Low Power Density 24 hr	50	100.0	3.50	52,000
Low Power Density 720 hr	50	970.0	55.00	87,000

[a]Silver zinc battery, manually activated

[b]Hydrogen-oxygen ratio, 4:1

[c]Hydrogen-oxygen ratio, 1:8

In most instances the historical cost data must be further analyzed to avoid certain pitfalls in its application. For example, the development program may be a continuation of a previous program, some of the major subsystems may have been developed on other programs, some of the subsystems such as mission equipment may have been GFE, or the historical costs shown may not reflect price level changes. Of major significance is whether the system management procedures (such as quality control or system test requirements) reflected in the contractor's costs are still applicable. These procedures may significantly increase or decrease costs. Perhaps the description and costing of various systems is not compatible with present system and cost descriptions. Perhaps the system checkout and test procedures are different. These are criteria that must be applied to the contractor's cost history to ascertain its applicability and the adjustments that may have to be made. In addition, it must be determined whether an industrial contractor's cost experience on one system can serve as a basis for estimating costs on a different type of system. Unless there is a prime and subcontractor relationship, the detail cost history of one industrial contractor may not be available to other industrial contractors, and each industrial contractor may also be limited in cost estimating by other factors such as:

a. The nature of his past business and present contracts
b. His method of accounting and availability of analyzed data
c. His methods and techniques for estimating
d. The complexity of the task
e. The time available for estimating
f. The importance of the program to the contractor's management

Whatever these limitations may be, industrial contractors are still expected to make maximum use of their own cost experience gained on their major programs.

4. EVALUATION METHODS AND TECHNIQUES

Assurance that the industrial contractor's effort meets the specified systems cost analysis and cost effectiveness requirement is best accomplished through frequent evaluation and monitoring of his progress.

Normal monthly technical direction meetings are generally not sufficient in time or in scope to evaluate the costing approach, methodology, and progress made by the contractor. These meetings need to be supplemented by special meetings to discuss specific topics such as ground rules, costing definitions and specific techniques for estimating development, production, and operating costs.

It should be recognized that in conceptual studies a contractor does not have the time, funding, or technical data to perform a detailed total system cost analysis for each of a large number of systems and configurations. The best approach usually consists of accomplishing an adequate system cost optimization on a limited number of configurations of alternative systems. The preferred system can then be further analyzed and evaluated in greater depth. If this approach is followed, consistency is the important factor.

The following sections provide a summary of some of the evaluation methods and techniques which are employed in the process of technical direction.

4.1 THE USE OF COST EFFECTIVENESS AS AN EVALUATION TOOL

Cost effectiveness evaluations are often used during the conceptual phases of a program. A part of this type of evaluation generally consists of developing mathematical cost models which predict cost as a function of the mission, performance, design, and operating variables. The increased size and complexity of systems and the number of alternatives considered makes the use of these cost models a necessity.

The specific objectives of cost effectiveness are at the present time not well defined in most proposal requests and in specific implementation instructions or procedures. To adequately perform cost-effectiveness a high degree of experience, knowledge, and creativity is required. There is a need to standardize definitions, technologies, and methods of approach.

The most difficult task in the evaluation process is to ensure that all significant system performance and cost factors are considered and that the evaluation is sensitive to critical cost assumptions made and the accuracy of the cost data incorporated into the models. The analysis is more difficult if specific budgetary constraints and definitive operational requirements for a mission are not available.

Proper evaluation of this task requires an understanding of the contractor's formulation of the problem. Some of the system concepts that should be considered are:

a. System reliability
b. Technical risk
c. Operational availability date
d. Growth potential
e. Survivability
f. Spacecraft design and performance features
g. Booster compatibility

The major criterion commonly shown is the relationship between total program cost and mission effectiveness. System and cost effectiveness can be shown by this criterion as functions of mission parameters. Table 3 lists the trade-offs that are possible in cost effectiveness optimization. Table 4 is a checklist for identification of accountable factors.

Technical risk may be analyzed on the basis of cost sensitivity to design and system cost uncertainties. The significance of critical technical parameters should also be indicated. The influence of size on design, performance, and costs is also an indicator of effectiveness that should be shown.

Table 3. Typical Trade-Off Areas for Cost Effectiveness Optimization (Ref. 2)

Resources	Variables	Alternatives
Funds Available	Cost	Basic Concept
Time Available	Weight	Multipurpose versus Single Purpose
Payload Capability	Payload Carried	Manned versus Unmanned
Manpower and Skills	Mission Length	Multiple Payload versus Single Payload
	State of the Art	Liquid versus Solid Rockets
	Time Required	Recoverable versus Non-recoverable
	Reliability	Systems and Subsystem Type
	Safety	Battery Power versus Fuel Cells
	Maintenance	Active versus Passive
	Availability	Spin Stabilized versus Three-Axis
	Vulnerability	System and Subsystem Configuration
	Survivability	Redundancy
		Field versus Depot Maintenance
		High Reliability versus MIL Standard Parts
		On-Orbit versus Ground Station Capabilities
		Operational Modes
		Resupply versus Single Mission
		Reusability versus Single Purpose

Table 4. Typical Checklist for Identification of Accountable Factors in Cost Effectiveness (Ref. 2)

- System Hardware Description
  - Modes of Operation
  - Hardware Organization
- Compatibility
  - (e.g., Electromagnetic Compatibility)
- Survivability
- Vulnerability
- Deployment
- Geographic Factors
  - Deployment
  - Geology
  - Climate
  - Atmospheric Phenomena
- Personnel
  - Operating
  - Maintenance
- Transportation
- Spares
  - Provisioning
  - Storage
  - Packaging
- Support Equipment
  - Test
  - Transport
  - Maintenance
  - Facilities
- Procedures/Policies
  - Operating
  - Repair
  - Inspection/Maintenance
  - Testing
- System Interfaces
  - Support Systems
  - Force Mix
  - Strategic Integrated Operations Plan

The Weapon System Effectiveness Industry Advisory Committee (WSEIAC) has listed in its final summary report a logical framework of fifteen steps for conducting system/cost effectiveness prediction and analysis. These steps are:

1. Define mission
2. Identify resources
3. Describe system
4. Specify figures of merit
5. Specify accountable factors
6. Identify data sources
7. Model construction
8. Data acquisition
9. Data processing
10. Specify schedule
11. Model exercise
12. Prepare management summary report
13. Decision process
14. Implementation decision
15. Change analysis

4.2 DEVELOPING AN INDEPENDENT SYSTEM COST ANALYSIS

An independent system cost analysis serves as a very useful comparative technique in validating the results of the contractor's efforts. If carried out in sufficient depth, this technique will indicate areas where the contractor may have overestimated or underestimated costs.

For this purpose, a comprehensive cost data bank and library containing historical and recent cost data on various subsystems and programs is essential. A file of existing system cost models and CER's is useful as an evaluation aid. The library of cost data should contain basic contractor cost and technical data contained in various proposals, progress reports, financial

reports, and study reports. The military program cost data should contain a summary of total program and various supporting system costs.

Each military system has a number of physical, performance, and cost characteristics which lend themselves to comparative analysis. Physical characteristics include weight, volume, power, shape, and number of systems or functions. Performance characteristics include speed, accuracy, range, and operational data. Cost data include development and acquisition costs. The historical data relating to these characteristics can be effectively summarized into a system cost analysis and cost effectiveness analysis which can be used as evaluation aids in comparing contractor estimates.

4.3 EVALUATING THE IMPACT OF REUSABILITY AND REFURBISHMENT

In performing a systems cost analysis, the contractor often finds that the entire economic analysis revolves about reusability and refurbishment costs and concepts. Compared with the costing of definitive programs in which quantities and operational concepts are well formulated, many SSD space systems studies require that these concepts be developed.

Since quantities to support a mission schedule will vary depending upon the reuse and refurbishment concepts adopted, the total space system cost is subject to large variances. These variances will occur since satellite and launch vehicle requirements are a function of over-all launch reliability, satellite mean time between failures, wearout life, and the number of satellites required on station. The number of satellites on station and the number of ground stations in the system are also a function of system availability and coverage requirements. When considering multipurpose and multiple payload type spacecraft, these considerations become more complex and require a comprehensive review of all assumptions and considerations before a proper economic evaluation or conclusion can be made. It is foreseeable that large numbers of flights for resupply of life support

equipment and expendable supplies and the rotation of crews to orbiting space stations will be accomplished by reusable vehicles.

The savings in operational costs can be significant as is illustrated by the flight program of the X-15. More than 150 flights have been completed by the three vehicles. Two have been recovered and reused more than 50 times, and the third has made more than 40 flights. The X-15 flight program is cited since it embraces both aeronautics and space flight and has been found by the NASA Flight Research Center to provide a base line for feasibility studies of reusable space vehicles.

In 1964 the total cost of 27 flights was $16.3 million. The cost per flight was $602,518; of this cost, the refurbishment cost was $270,000 or 45 percent of the total cost per flight. Since the cost of a new X-15 is approximately $9 million, the refurbishment cost is only 3 percent of the vehicle cost.

The refurbishment cost analysis should be based on vehicle design characteristics such as component life expectancy, degradation of electrical and mechanical systems, and structural fatigue and replacement. Costs of various equipment items along with costs of integration and testing should be clearly identified.

This type of analysis may be directed toward developing a refurbishment cost model for space vehicles in which refurbishment costs will vary with the number of flights.

4.4 RELATING COSTS TO THE PROGRAM SCHEDULE

From project initiation to operational status of a new space system usually takes a minimum of two to four years. However, if the program requires significant state-of-the-art development such as that found in Nike-Zeus, Sprint, and Apollo, more development time will be required to bring the system to operational status.

Since RDT&E costs are largely a function of engineering manpower, most cost uncertainties are reflected in either more people required for the same time or the same people for a longer time. All major contractors are keenly aware that maintaining the planned schedule is the key to cost control. However, in a study program, the evaluation must focus on the reasonableness of the schedule spans, the manpower levels indicated, and the major milestones established. The preparation of a detailed program schedule to the subsystem design, development, testing, and manufacturing level is usually beyond the scope of the study effort and the funds and information available.

However, the minimum requirement expected in the technical direction is a master program schedule which provides a general summary of major milestones related to accomplishment of program objectives. The development plan should also define development requirements, test objectives, and development philosophy.

The development plan and schedule must then be integrated and compared with the system cost analysis to ensure that costs and schedule are interrelated. Too often the cost analysis is performed independent of the schedule and in some instances independent of the technical analysis.

5. EVALUATING THE STUDY RESULTS

The general requirement of the technical evaluation and direction effort is to ensure that a feasible technical and cost approach to the objectives of the study is established and carried out.

From the conclusions and recommendations of the contractor's study a Tentative Specific Operating Requirement (TSOR) may be developed. This TSOR may lead to subsequent study or to the project definition, acquisition, and operational phases of the program. Some of the basic plans and proposals that will require system cost analysis in subsequent phases include:

a. Technical Development Plan
b. System Package Plan
c. Operating Plan
d. Contractor's Proposals

A final evaluation technique is to analyze the degree to which previously developed subsystems are included in the system being studied. For example, new subsystems are likely to cost as much to develop as the previous subsystems. Costs to modify previously developed systems will generally run from 10 to 50 percent of the original development cost. Experience has shown that production costs will vary less.

A review of the operational philosophy, system requirements, and constraints should also be made. This review should be evaluated against the system cost analysis and schedule to assure proper program phasing. Further evaluation criteria may require the estimation of budgetary constraints for the proposed program. This may be accomplished by referring to the Department of Defense Appropriations or the Force Structure and Financial Plan.

The final evaluation is generally limited to a short period - usually not more than one month. It is, therefore, necessary to ensure that adequate progress is made throughout the study effort, since only highlights, summaries, and comparative type analyses can be made during this final evaluation period.

6. SUMMARY AND CONCLUSIONS

This report has presented a discussion of the significant aspects of the technical direction and evaluation effort as related to space systems cost analysis performed by industrial contractors in study programs.

It has stressed some of the steps and procedures required to ensure that the final product of the industrial contractor's effort meets the quantitative and qualitative level of total system analysis needed by the U. S. Air Force as a basis for sound long range planning.

Throughout this report, technical direction and evaluation has been defined in terms of the necessary organization, definition, and approach to the cost aspects of the system under study. Common pitfalls in systems cost analysis have been presented in order to indicate the guidance necessary to industrial contractors.

The uses and limitations of industry cost models, CER's, and other estimating methods have been described. A comprehensive and consistent approach, including an independent cost analysis as a comparative evaluation technique, has been advocated. The need for defining and understanding the various analytical costing methods and the proper use of historical cost information have also been emphasized. Various guidelines have been provided on the approach and techniques used to initiate the industrial contractors' system cost analyses, and also to review their progress and the final reports.

In conclusion, a combination of engineering and systems cost analysis experience and skills has been shown to be a vital requisite to proper accomplishment and validation of the industrial contractor's effort. The relationships established between cost and system performance have also been shown as forming the framework of any future development, acquisition, and

operation of a new space system. The technical direction and evaluation effort is performed to ensure that these relationships are reasonable, valid, and adequately supported.

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APPENDIX A

DEFINITIONS[1]

A.1 DEFINITIONS FOR ELEMENTS OF A SPACE SYSTEM

Space Category - Those systems related to the placement, operation, and recovery of systems in space. This includes launch vehicles, various space orbiting and reentry payloads as well as launch, flight, and recovery operations where appropriate. Both manned and unmanned systems are included.

Space System - The complex of equipment, software, services, and facilities required to develop and produce the capability for the placement, operation, and recovery of manned and unmanned vehicles and equipment in space. Represented by those launch vehicles, orbiting payload and support equipment, and space vehicles and reentry systems such as Titan II, Satcom; and MOL, START, ABRES, AGENA, respectively.

Space Vehicles - Complete vehicle or group of vehicles placed in space. Includes the structure, propulsion and all installed equipments. Includes design, development, and production of complete units (prototype and operationally configured units which satisfy the requirements of its applicable specification(s), regardless of their end use).

Spacecraft/Satellite - The principal operating space vehicle containing the basic space structure, shroud where appropriate, propulsion, power supply, attitude control, communications, navigation and guidance, crew

[1] Based on Summary Work Breakdown Structure and Definitions - Space System, Proposed MIL-STD prepared by Office of Secretary of Defense (30 September 1966).

accommodations for manned spacecraft, etc. The spacecraft/satellite is usually a self-sufficient operating unit.

Special Payload (if applicable) - That payload equipment provided for special purposes in addition to the normal payload integral to the spacecraft. For example, experiments placed aboard the MOL spacecraft are considered special payload.

Reentry Vehicle - The space vehicle specifically designed to safely reenter the atmosphere in order to land special payload or crew. Includes the structure, propulsion and all installed equipments.

Orbit Injection/Dispenser System - The equipment, usually packaged separately, which performs the function of placing satellite vehicles in the planned orbit. Includes the structure, propulsion or charge, instrumentation, etc.

Flight Crew Equipment - The personal equipment of the flight crew for manned space vehicles. Includes space units, life support equipment, and other auxiliary equipments for safety, propulsion, and communications.

A.2 DEFINITIONS OF COST CATEGORIES AND COST ELEMENTS FOR SPACE SYSTEMS

A.2.1 Research, Development, Testing, and Evaluation Costs

Research and development are primarily associated with the development to a point where it is ready for acquisition.

Cost Elements

1. Systems Engineering and Integration - All feasibility, research, and development activities directly contributing to the over-all system and all scientific and engineering services to integrate the entire project. Examples of specific systems engineering activities are: Special Studies, Systems Analysis, Systems Integration, Human Engineering/Life Support,

QQPRI, Safety Engineering, Value Engineering, Logistics Support Program, Maintainability Program, Quality Assurance Program, Reliability Program, System Test Plans and Objectives, General Systems Engineering/Technical Direction, Advance Product Engineering, Production Planning and Analysis, Facility Design, Weighing, Engineering Calculations, and Special Weapons/AEC Coordination.

2. Spacecraft and Trailer (Propulsion and/or Cargo) Engineering, Design, and Development Testing - Spacecraft engineering, laboratory testing, shop and vendor liaison engineering, tooling and special test equipment mockups, technical data and special test articles including all subsystems except main propulsion engines, astrionics, and crew support. Also includes cost of integrating engine, astrionics, and payload and crew support systems, plus integration with the launch vehicle.

3. Engine Design and Development - Engineering, tooling, special test equipment, facilities, test hardware, and propellants for engine development through qualification.

4. Astrionics Design and Development - Engineering, tooling, special test equipment, laboratory testing, and test hardware costs for the spacecraft astrionics subsystem including related environmental control. Mission peculiar (payload) astrionics development costs are not included.

5. Spacecraft Personnel Support Subsystem Design and Development - Engineering, design, tooling, facilities, equipment mockups, and test hardware to develop those support subsystems (i.e., life support, data display, controls, etc.) which are required to integrate man into the spacecraft.

6. Launch Vehicle Modifications - Engineering, tooling, and equipment required by the launch vehicle contractors to design and develop the spacecraft/launch vehicle mechanical and electrical interface; includes all necessary vehicle modifications to support the mission.

7. <u>Ground Test Operations</u> - Cost of all ground test operations which include dynamic, all-systems, flight test support, and production acceptance testing.

8. <u>Flight Test Operations</u> - Cost of the flight test program including spacecraft transportation, spacecraft/launch vehicle assembly, and checkout, recovery, refurbishment, plus launch and recovery base support.

9. <u>Ground and Flight Test Hardware</u> - Spacecraft and trailer, airframe, engine, astrionics and personnel support hardware plus the required launch vehicle costs incurred to support the ground and flight test programs. Includes dynamic, all-systems facility checkout, flight, and inert test units.

10. <u>Design, Development, Fabrication, and Installation of Spacecraft AGE</u> - All spacecraft peculiar equipment (excluding payload) for transportation, servicing, testing, checkout, recovery, and refurbishment.

11. <u>Design and Construction of Spacecraft Related Launch Site Facilities</u> - Cost of design and fabrication of spacecraft peculiar launch site facilities, including a new or expanded control center, instrumentation center, data transmission lines, and propellant and high pressure gas storage tanks and transfer lines; plus spacecraft related launch support facilities (including assembly and checkout, service towers, spacecraft personnel support, etc.).

12. <u>Design and Construction of Spacecraft Recovery Facilities</u> - Cost of all facilities and equipment required for the selected recovery areas. Includes site preparation, mission and operational support hardware storage facilities, plus facilities to house handling and landing control equipment.

13. <u>Design and Construction of Spacecraft Refurbishment Facilities</u> - Cost of all facilities required to support refurbishment operations of the spacecraft subsystems and structure, including storage facilities.

14. Program Management - The process of planning, organizing, coordinating, controlling, and approving administrative actions designed to accomplish over-all project objectives. Examples of specific program management activities are: Configuration Management, Cost/Schedule Management, Data Management, Project Office, Contractor Compliance, Vendor Liaison, and the Transportation and Packaging Program.

A. 2. 2 Initial Investment Costs

Production of flight articles and supporting equipment in accordance with the required rate to support the operational program.

1. Operational Spacecraft Flight Hardware

a. Spacecraft Structural Assembly - Included in this element are: (1) structural components, (2) landing gear, (3) control surfaces, (4) launch vehicle/spacecraft interface structure, and (5) all minor subsystems not included in personnel support, propulsion, astrionics, or thermal protection subsystems.

b. Spacecraft Propulsion - Includes main propulsion engine manufacture up to system integration by spacecraft contractor, tooling, and technical assistance.

c. Spacecraft Thermal Protection Subsystem - Included are the basic heat shield structure, structural cooling systems, hatch and window modifications, and crushable honeycomb on the heat shield of a vertical landing spacecraft (if required).

d. Spacecraft Astrionics - Included in this element are the following subsystems: power and electrical distribution, navigation, guidance, tracking, control, separation, range safety, equipment environmental control, instrumentation, and abort.

e. Spacecraft Personnel Support - Included are manned mission environmental control, nutrient subsystems, displays and controls, and those sundry requirements imposed by normal and emergency life support conditions for the concept involved. Mechanical emergency abort subsystems are specified in the spacecraft structural assembly cost element.

2. Launch Vehicle - Cost of the launch vehicles required to boost the spacecraft into orbit.

3. Initial Spares - Initial quantity of airframes, engines, astrionics, and spacecraft crew support subsystem spares produced to support the operational program.

4. Training - Training services, devices, accessories, aids, equipment, and parts used to facilitate instruction through which personnel will acquire sufficient concepts, skills, and attitudes to operate and maintain the system with maximum efficiency. Includes all effort associated with the design, development, and production of training equipment as well as the execution of training services.

5. Fabrication and Installation of Additional Spacecraft and Launch Vehicle AGE Required to Support Operational Program - Cost of manufacture, installation, and test of the additional AGE required for the spacecraft at the launch site and payload integration areas, recovery areas, refurbishment areas, and for transportation and handling.

6. Spacecraft and Launch Vehicle Operational Support Facilities - Cost of those additional facilities required for operational spacecraft recovery and refurbishment, plus additional launch area facility costs for both the spacecraft and launch vehicle.

A.2.3 Operational Costs

Covers period from acceptance of the first operating unit until disposition of the system.

1. <u>Spacecraft Transportation</u> - Included in this element are the cost of transporting spacecraft components from their manufacturing and/or storage sites to the launch or test site and the cost of transporting the spacecraft and its related equipment from the recovery area and subsequently to the launch or storage site.

2. <u>Spacecraft Prelaunch and Launch Operations</u> - Cost to receive, inspect, test, assemble, check out, maintain, and mate the spacecraft to the launch vehicle. Includes all routine launch related spacecraft operations except payload related costs.

3. <u>Launch Vehicle Prelaunch and Launch Operations, Propellants, and Subsystem Spares</u> - Cost for the operational program launch and prelaunch activities directly related to the launch vehicle including the required propellants plus required minor subsystem spares to support the operational program.

4. <u>Spacecraft Recovery Operations</u> - Cost to support the operations at the designated recovery areas.

5. <u>Spacecraft Refurbishment Operations</u> - Cost of sustaining spares required to restore the spacecraft and its subsystems to a flight-ready condition; includes preventive maintenance, repair, and checkout of the spacecraft systems. Payload related costs are not included.

6. <u>Spacecraft Propellants</u> - All propellants and gases delivered to the launch site to support spacecraft launch and prelaunch operations.

7. <u>Operational AGE and Facility Maintenance</u> - Cost required to maintain all test, launch, recovery, and refurbishment spacecraft related facilities and equipment in operating condition.

8. <u>Sustaining Engineering</u> - Cost incurred during the operational program to support hardware manufacture.

9. <u>Recurring Training Services and Equipment</u> - Cost of fabrication, installation, and checkout of the necessary concept peculiar training aids and equipment.

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13 ABSTRACT

Economic and cost effectiveness analyses of proposed system concepts have become vital requirements in virtually all U.S. Air Force Space Systems Division studies. Since development of a space system is extremely costly, lead time is lengthy, and budget limitations are severe, there is a clear need to forecast the total systems cost and effectiveness of a proposed new system as early in the planning cycle as possible.

This report presents highlights of the significant aspects of technical direction efforts in systems cost and cost effectiveness analyses. Major objectives of this effort are to ensure that the industry contractor:

a. Performs a total system cost analysis of sufficient depth and validity to permit analysis and evaluation

b. Identifies those operational design and hardware concepts which will provide the greatest savings in total systems cost

c. Properly validates those significant concepts and cost relationships which will lead to the selection of an optimum configuration

Recommendations on the approach and techniques to fulfill these objectives are provided. The uses and limitations of industry cost models, cost estimating relationships, and other estimating methods are discussed. Common pitfalls in system cost analysis are illustrated to indicate the guidance necessary.

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14. KEY WORDS

Costing Assumptions

Cost Effectiveness

Cost Estimating Relationships (CER's)

Cost Evaluation

Cost Research

Economic Analysis

System Cost Analysis

Abstract (Continued)

A combination of engineering and economic analysis experience and skills is shown to be a vital requisite to proper accomplishment and validation of the industrial contractor's effort.

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